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TIME-SERIES AND SPATIAL TRACKING OF POLLUTED CANAL WATER INTRUSION INTO WETLANDS OF A NATIONAL WILDLIFE REFUGE IN FLORIDA, USA

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Abstract: The discharge of nutrient and ion-enriched agricultural and urban runoff into perimeter canals surrounding the Arthur R. Marshall Loxahatchee National Wildlife Refuge and subsequent intrusion into a natural soft-water marsh is causing ecosystem alterations. Because this habitat is among the last remaining rainfall-driven areas of the Florida Everglades, understanding the dynamics of canal water intrusion is important for marsh protection and restoration. Using conductivity sondes, we examined canal water movement in and out of the marsh along four transects based on 350 and 500 µS cm^{-1} conductivity isopleths. Canal water intruded into the marsh to different extents, with the greatest intrusion observed on the west side of the refuge. Canal water was always evident in the marsh, and the maximum measured intrusion was 3.9 km from November 2004 through January 2006. Stage differences between the canal and marsh influenced the movement of water into and out of the marsh, with high inflow rates in the canal increasing intrusion into the marsh. Marsh areas with sediment elevations $<$ 4.9 m were most sensitive to canal water movement. Our analyses will contribute to the understanding of hydrologic conditions that lead to pollutant intrusion into floodplain wetlands.

Key Words: chemical indicators, conductivity, eutrophication, Everglades, Loxahatchee National Wildlife Refuge, tracers, water quality

INTRODUCTION

The Arthur R. Marshall Loxahatchee National Wildlife Refuge (Loxahatchee Refuge or refuge) is a 583 km^2 remnant of the Florida Everglades that is threatened by eutrophic and mineral-enriched canal waters that surround it (Figure 1). Rainfall and natural sheetflow were the primary sources of water to the Loxahatchee Refuge prior to its physical separation from the greater Everglades by the creation of perimeter levees and canals. Presently, urban and agricultural runoff discharged to the Loxahatchee Refuge through an intricate water management system makes up a significant amount of the overall water budget. These nutrient and mineral-enriched waters have the potential to move into the marsh from perimeter canal overflow, threatening the naturally oligotrophic ecosystem (USFWS 2000).

Monitoring in the Loxahatchee Refuge has improved our understanding of how canal water influences environmental conditions both spatially and temporally. The monitoring approaches varied from synoptic observations of surface water in the Loxahatchee Refuge and perimeter canals (Richardson et al. 1990, Reddy et al. 1998, Stober et al. 1998, McCormick et al. 2000, Scheidt et al. 2000, Stober et al. 2001, Childers et al. 2003, Harwell et al. 2005, Iricanin 2005, Sklar et al. 2005) to highly selective tracking of canal inflow events and their impact on specific areas of the marsh (McPherson et al. 1976). Combined, these studies show that there is a decreasing nutrient and mineral gradient from the canals to the interior of the marsh and canal water is the source of the gradient. However, these studies were not designed to capture the continuous dynamics of the canal and marsh interactions. The lack of this continuous monitoring leaves many unanswered questions, which include: What canal inflow rates influence canal water intrusion into the marsh? and What canal inflow rates or canal stages can be used and still maintain minimal canal water intrusion?

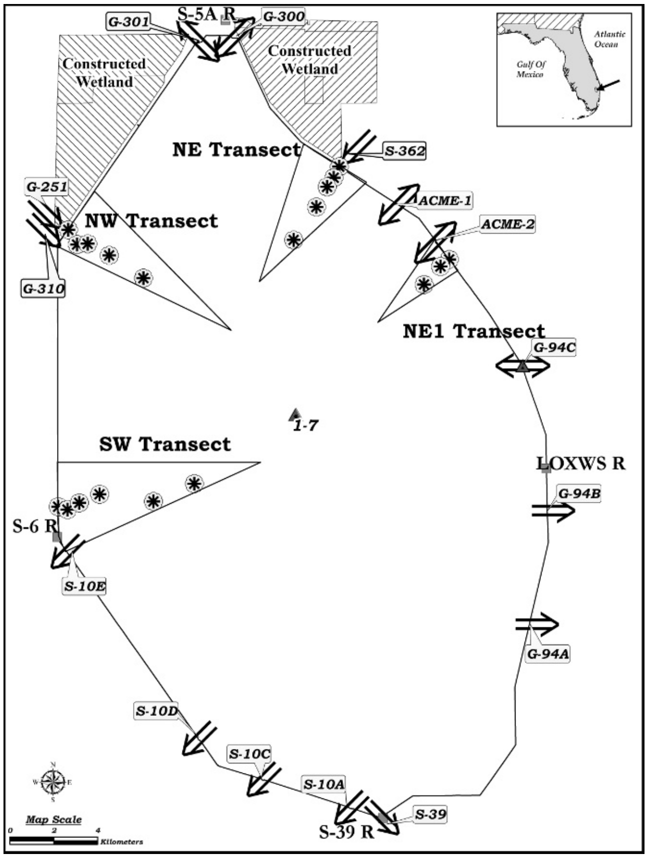

Figure 1. Map of the A.R.M. Loxahatchee National Wildlife Refuge as part of the northern Everglades (see inset). Individual sites (solid asterisks) along each of four transects (outlined by hollow triangles), canal flow sites (arrows), weather stations (solid squares), and stage gages (filled triangles) are presented.

Presently, water high in nutrients and minerals is discharged into perimeter canals from stormwater runoff and other sources. Because of the elevated canal nutrient and mineral conditions, there is a concern that when canal stage, mostly controlled by canal inflow, is greater than the stage in the marsh, enriched water from perimeter canals will intrude into the marsh, causing eutrophication and elevated ion concentrations in the marsh (Swift 1981, Swift 1984, Richardson et al. 1990, McCormick and Crawford 2006). The difference between canal and marsh stage had been assumed to be the dominant reason for canal water intrusion (Harwell et al. 2005, USFWS 2007). Alternatively, when canal water levels are < 4.7 m msl (NGVD 1929 unless otherwise specified), it has been hypothesized that minimal exchange of water between the canals and the marsh occurs (Sylvester 2004).

Pollution of Everglades wetlands, including the Loxahatchee Refuge, became the subject of a Federal environmental lawsuit (Case No. 88-1886-CIV-MORENO). The resulting settlement agreement focused on restoring water quality by improving the quality of water entering the Everglades, while still providing for other hydrological needs. Therefore, for water management of the Loxahatchee Refuge to be effective, we must understand the linkages between management of the canals and the resulting environmental conditions in the marsh. This study quantifies canal water flow into and out of the refuge interior habitat using conductivity as a tracer of canal water movement (as done by Sklar et al. 2005). By using sondes to continuously monitor conductivity, we associate conditions in the refuge marsh with canal water management.

METHODS

Rainfall, Stage, and Flow Data

Rainfall, stage, and flow data were downloaded from the South Florida Water Management District (SFWMD) data web portal, DBHYDRO, for the 15-month study period from November 2004 through January 2006 (http://www.sfwmd.gov/org/ema/dbhydro/). Rainfall data from four weather stations (S-6, S-39, LOXWS, and S-5A) were used for this analysis (Figure 1). Daily rain records were averaged for the four weather stations.

Marsh water levels were determined from a stage gage (1–7) in the center of the Loxahatchee Refuge (Figure 1). Previous work shows that water level patterns observed at the stage gage are the same as those throughout the marsh interior (Darby 2004). Canal stage was determined from a gage (G-94C) located along the eastern perimeter canal. Because of small inconsistencies between gage datums, the canal stage readings were adjusted by adding 0.028 m (USFWS 2007). Because of micro-topographic variations within the marsh (Kadlec 1990, Brandt et al. 2000, Choi et al. 2003), water movement between the canals and marsh at specific sites may differ from the general pattern inferred from these two gages. Therefore, differences between marsh and canal stages should be considered as general conditions.

Daily average canal inflow and outflow rates (m^3 s^{-1}) were used to determine the effects of canal water management on marsh and canal stage differences. Canal inflow and outflow records for all water management gates and pumps (G-251, G-310, S-362, G-300, G-301, ACME-1, ACME-2, S-39, S-10E, S-10D, S-10C, and S-10A; Figure 1) were summed to calculate the daily total of all canal inflows and outflows.

Table 1. Distance from the canal into the marsh for the southwest (SW), northwest (NW), northeast (NE), and northeast 1 (NE1) transects.

Transect	Site ID	Distance from canal (km)	Transect	Site ID	Distance from canal (km)
SW	LOXA115	Canal	NE	LOXA135	Canal
	LOXA116	0.4		LOXA136	0.6
	LOXA117	0.9		LOXA137	1.1
	LOXA118	1.8		LOXA138	2.1
	LOXA119	4.3		LOXA139	3.9
	LOXA120	6.1	NE1	LOXA129	Canal
NW	LOXA104	Canal		LOXA130	0.5
	LOXA105	0.7		LOXA131	1.5
	LOXA106	1.1			
	LOXA107	2.2			
	LOXA108	3.9			

Conductivity Data

Nineteen conductivity sondes (Hydrolab, Mini Sonde 4a; YSI, Series 6MLX) were deployed (Table 1; Figure 1) along four transects from the perimeter canals to 4 km into the marsh (Brandt et al. 2004, Harwell et al. 2005, USFWS 2007). Sondes recorded specific conductivity at hourly intervals. Each sonde was collected monthly or bimonthly for data download, post-deployment calibration, cleaning, re-calibration, and re-deployment. Periodic data gaps resulted from insufficient water depths and sonde malfunctions.

Distance of Intrusion

We define intrusion as any event in which high conductivity ($\geq$ 700 μS cm^{-1}) water overflows perimeter canal banks and moves into the marsh, which typically has low conductivity levels ($<$ 150 μS cm^{-1}) (USFWS 2007). Intrusion was quantified by following the movement of conductivity isopleths along four transects (northeast [NE], northeast one [NE1], northwest [NW], and southwest [SW]), which extend from the perimeter canal into the marsh interior. Three of these transects (NE, NE1, and NW) were located adjacent to present canal water inflow sites, while the fourth transect (SW) was located adjacent to a historical canal inflow site. This transect was included because low sediment elevations in the southwest region of the refuge may result in high intrusion of canal water from upstream sources.

The location of the 500 and 350 μS cm^{-1} isopleths was used to determine the spatial and temporal extent of canal water intrusion into the marsh. The isopleth locations were estimated by interpolating between conductivity data points along transects. The location of these isopleths indicates canal water movement into the marsh interior, as well as movement of water from the interior marsh towards the perimeter canals.

Conductivity typically is less than 150 μS cm^{-1} in the rainfall-driven areas of the marsh (generally $>$ 4.5 km from the canal) (Richardson et al. 1990, USFWS 2007). Conductivity in the canals generally ranges from 700–1,000 μS cm^{-1} (Richardson et al. 1990, USFWS 2007), allowing for conductivity to be used as a tracer of canal water movement. The 500 and 350 μS cm^{-1} conductivity levels were chosen as reference values for both data visualization and ecological reasons. First, the 500 and 350 μS cm^{-1} conductivity levels clearly are in between typical values for canal water and unimpacted marsh water. Second, preliminary results from an experimental study testing the ecological impact of full concentration (1,000 μS cm^{-1}) and 50% (500 μS cm^{-1}) canal water indicate that canal water diluted to 50% affects growth and development of native plants (e.g., *Xyris ambigua*; McCormick and Crawford 2006). The 350 μS cm^{-1} value was chosen because other experimental research documents that soft-water periphyton community changes when low conductivity areas are exposed to conductivities in the range of 300 to 400 μS cm^{-1} (Sklar et al. 2005). Thus, the 500 and 350 μS cm^{-1} isopleths suggest locations where canal water impacts to marsh vegetation may occur.

RESULTS

Environmental Conditions

Marsh Sediment Elevation. Marsh sediment elevation in the Loxahatchee Refuge was highest in the north and lowest in the southwest (Figure 2). Marsh sediment elevation along transects was lowest near the canal and increased farther into the marsh, and the lowest elevation was observed along the southwest transect. In general, the east marsh edge

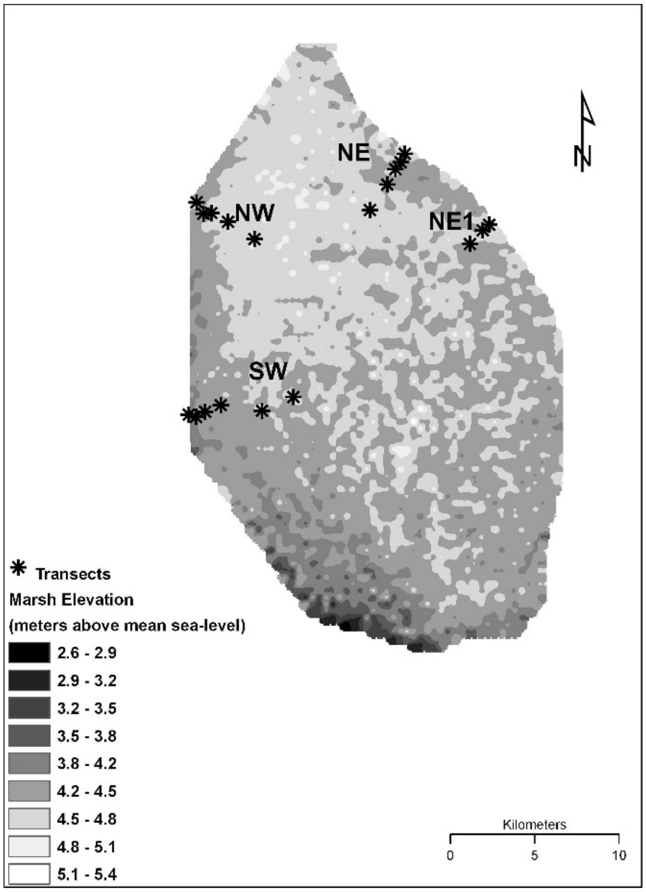

Figure 2. Marsh sediment elevation map of the A.R.M. Loxahatchee National Wildlife Refuge (see Figure 1), the four transects (SW, NW, NE, and NE1), and sites (asterisks) within those transects. Topography is based on digital elevation data from USGS (2005).

had higher elevations than the west marsh edge, and interior elevations were higher than marsh edge elevations. There are micro-scale topographic differences across the marsh, and these differences may create barriers for water movement, particularly when water levels are low (Choi et al 2003).

Rainfall. Rainfall on the Loxahatchee Refuge averaged 1.07 m yr^{-1} and contributed 69% of the total volume of water entering the area (Table 2). Rainfall was most frequent between May and early September 2005. Extreme rainfall events resulting from storm events occurred in June (unnamed storm) and October (Hurricane Wilma) 2005.

Canal Inflow and Outflow. Average daily inflow to the perimeter canals was 10 $\pm$ 16 $m^3\ s^{-1}$ for the study period. Approximately 80% of this inflow was on the west side of the marsh, while the remainder was on the east side. The maximum daily inflow (117 $m^3\ s^{-1}$) occurred in early June 2005. Inflow also was high (55 $m^3\ s^{-1}$) at the end of June and October 2005 and sporadically throughout the year (USFWS 2007). Average daily and maximum outflow was 10 $\pm$ 14 $m^3\ s^{-1}$ and 79 $m^3\ s^{-1}$, respectively. Outflows two and three times greater than inflows occurred sporadically throughout the study period, but were most frequent from April through July 2005.

Canal and Marsh Stage Relationships. Average canal stage was 4.95 m with a range of 4.63–5.19 m, and average marsh stage was 4.97 m with a range of 4.77–5.17 m. The canal stage exceeded marsh stage by a maximum of 0.16 m, while marsh stage exceeded canal stage by a maximum of 0.33 m. Marsh stages were above average from June through December 2005. Canal stages were above average sporadically through the year, particularly from September through December 2005.

Interrelated Environmental Conditions

The temporal patterns of rainfall, canal inflow and outflow, and canal and marsh stages are related

Table 2. Environmental conditions including inputs (canal inflow plus rainfall), outflow, and marsh and canal stage summary statistics from November 2004 through January 2006.

	Percent of Total Input	Percent Canal Inflow	Input Rate ($m^3\ yr^{-1}$)	Standard Deviation ($m^3\ yr^{-1}$)
Rain	69%		773.7×10^6	42.5×10^6
Inflow	31%			
STA-1W		64%	219.5×10^6	13.2×10^6
STA-1E		11%	38.0×10^6	3.6×10^6
ACME-1		6%	19.2×10^6	1.6×10^6
ACME-2		4%	14.6×10^6	1.3×10^6
Bypass		15%	49.7×10^6	12.1×10^6
			Outflow Rate ($m^3\ yr^{-1}$)	Standard Deviation ($m^3\ yr^{-1}$)
Outflow			356.9×10^6	29.1×10^6
	Mean Stage (m)	Minimum Stage (m)	Maximum Stage (m)	
Marsh	4.97	4.77	5.17	
Canal	4.95	4.63	5.19	

Table 3. Transect-specific summary statistics for intrusion distances and associated hydrological conditions.

Transect	Average 500 μS cm^{-1} Intrusion (km)	Maximum 500 μS cm^{-1} Intrusion (km)	Average 350 μS cm^{-1} Intrusion (km)	Maximum 350 μS cm^{-1} Intrusion (km)	Date	Canal Stage > Marsh Stage by (m)	Net Inflow (m^3 s^{-1})
SW	0.8 ± 0.6	2.5	1.4 ± 1.0	3.9	Nov-05	0.06	4
NW	0.7 ± 0.2	1.9	1.1 ± 0.4	2.7	Jun-05	0.07	32
NE	0.4 ± 0.2	1.9	0.8 ± 0.4	2.6	Jun-05	0.07	32
NE1	0.6 ± 0.4	1.4	0.7 ± 0.5	1.5	Jun-05	0.07	32

to each other. When rainfall occurs upstream of the refuge, canal inflows to the marsh increase because of increased runoff. Increased inflows result in increased canal and marsh stages and/or increased outflows.

Regional rainfall, canal inflows, and peak marsh stages were lower than normal during the study period, resulting in relatively short hydroperiods in the northern areas of the refuge (USFWS 2007). In addition to drier-than-usual conditions, water management operations contributed to relatively low inflows (USFWS 2007).

Canal Water Intrusion

The 500 and 350 μS cm^{-1} isopleths along the west transects increased above average (Table 3) beginning in early October 2005 and lasted through the year (Figure 3c through 3f). On the west side (Figure 3c and 3d), increased intrusion occurred a few weeks to a month earlier than on the east side (Figure 3e and 3f).

Maximum intrusion for the 500 μS cm^{-1} isopleth (2.5 km) and 350 μS cm^{-1} isopleth (3.9 km) along the SW transect occurred at the end of November 2005 (Figure 4; Table 3). Maximum intrusion for the other three transects occurred in early June 2005. Maximum intrusion of the 500 μS cm^{-1} isopleth was 1.9 km along the NW and NE transect and 1.4 km along the NE1 transect. Maximum intrusion the 350 μS cm^{-1} isopleth was 2.7 km along the NW transect, 2.6 km along the NE transect, and 1.5 km along the NE1 transect.

With the exception of the NW transect near the canal inflow site, intrusion was lowest from July through September 2005 (Figure 3). During this period for the NE and NE1 transects, the 500 and 350 μS cm^{-1} isopleths remained at or below 0.5 km into the marsh. From July through August 2005, intrusion of the 500 and 350 μS cm^{-1} isopleths was below 0.5 km. By September 2005, the 500 μS cm^{-1} intrusion extended to 0.6 km and the 350 μS cm^{-1} isopleth intrusion extended to 0.7 km; however, these distances were below average for each transect.

DISCUSSION

This study demonstrated that continuous monitoring of conductivity can be a useful tool to track water movement in and out of marshes. We documented several strong influences on timing and distance of perimeter canal water intrusion into the study marsh including: 1) relative magnitude of

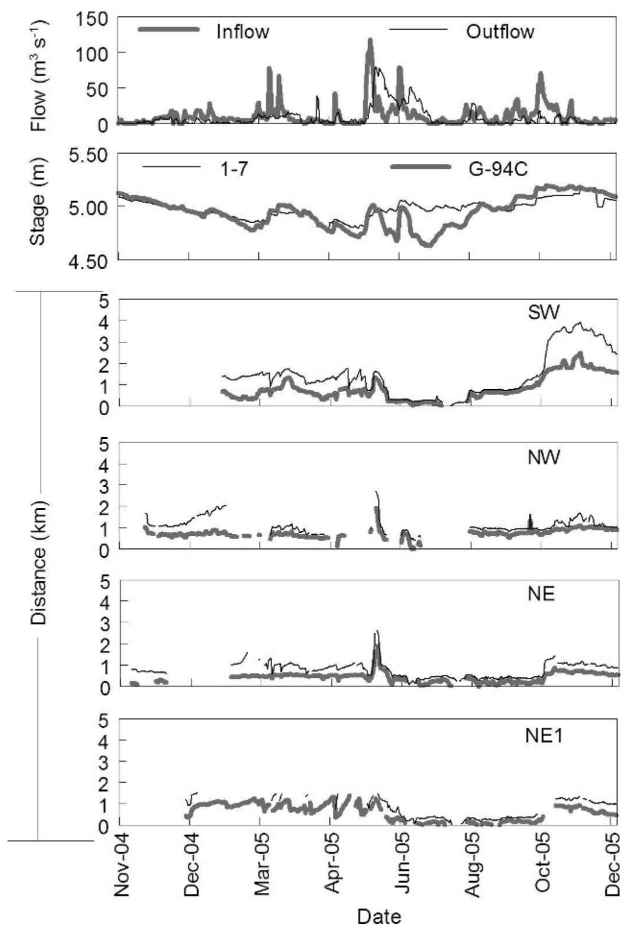

Figure 3. Time-series of environmental conditions (A and B) and intrusion along the four transects (C through F). A) Inflow (thick line) and outflow (thin line), B) canal stage (thick line) and marsh stage (thin line) are presented. The 500 (thin line) and 350 (thick line) μS cm^{-1} isopleths are presented for the C) SW, D) NW, E) NE, and F) NE1 transects.

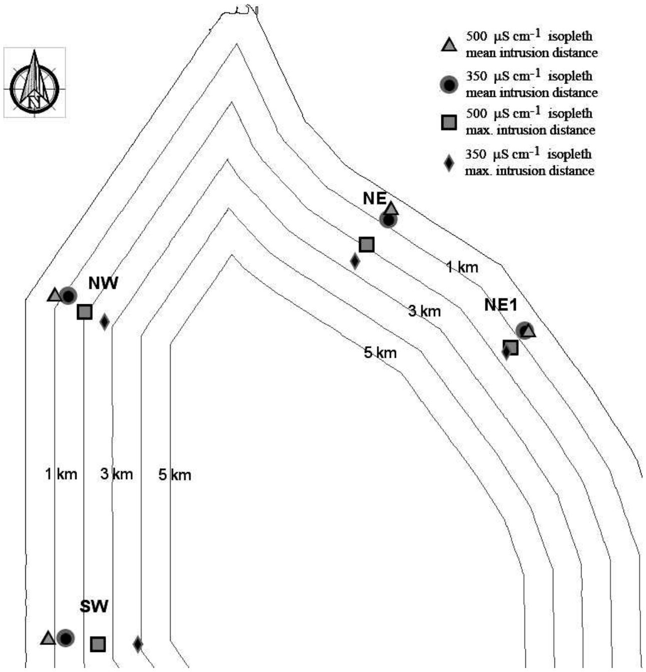

Figure 4. Maximum and average intrusion distances between November 2004 and January 2006. Squares represent maximum intrusion distance following the 500 μS cm^{-1} isopleth; diamonds represent maximum intrusion distance following the 350 μS cm^{-1} isopleth; triangles represent average intrusion distance following the 500 μS cm^{-1} isopleth; and circles represent average intrusion distance following the 350 μS cm^{-1} isopleth. Outer rings delineate 1 km increments of distance from canal.

canal inflows and outflows; 2) duration of canal flows; and 3) stage differences between the canal and marsh. Knowledge of how canal water intrusion is influenced by inflow, outflow, and differences between canal and marsh stages can be applied to improve water management operations to reduce impacts of eutrophic canal water on a historically rainfall-driven marsh.

Influence of Canal Inflows and Outflows on Intrusion

Inflows to perimeter canals can push canal water into the marsh, and the distance of intrusion is associated with the inflow rate. High inflow rates were related to greater distances of intrusion than low inflow rates. For example, during one high inflow event in June 2005 ($> 116\ m^3\ s^{-1}$), intrusion in the north extended to more than 2.5 km (Table 3). The high inflow to the perimeter canals came from three canal inflow sites in the north, two on the west side and one on the east side. These inflows were sufficient to push most of the discharged water over any micro-topographic barriers and into the marsh.

When inflows were low to moderate, intrusion still occurred along all transects, with the greatest intrusion occurring on the west side. From mid-November through the end of November 2005, intrusion increased to 3.9 km in the SW, 1.7 km in the NW, and 1 to 1.3 km in the northeast areas (Table 3). This intrusion event was influenced by high inflow rates on the west side, with little or no inflow on the east side.

An opposite pattern was observed in late June 2005 when high canal outflow decreased canal stages, allowing marsh interior water to move towards the canals, thus reducing canal water intrusion. Another example occurred from March through April 2005, when canal inflows and rainfall were low and canal and marsh stages were declining. Even when canal outflow was low to moderate ($6\ m^3\ s^{-1}$ to $20\ m^3\ s^{-1}$), average or below average canal water intrusion could be observed along each transect (Figure 3).

The final pattern observed was when high inflow was followed by high outflow (equal to or greater than the inflow) and intrusion was reduced. This pattern was observed in early June 2005 when intrusion in the northern area of the marsh increased for a few days and then rapidly decreased (Figure 3).

Impact of Flow Duration on Intrusion

The duration of inflow influences the magnitude and duration of canal water intrusion into the marsh. Short periods ($<$ 4 days) of high inflow resulted in short duration peaks in intrusion distance, and these intrusion events would dissipate more rapidly than during extended inflow periods. For example, a short period of increased inflow occurred in March 2005, when inflows were very high ($> 55\ m^3\ s^{-1}$) for one day, yet intrusion was average for most transects (Figure 3).

Not unexpectedly, long inflow durations resulted in long durations, and sometimes large magnitudes, of canal water intrusion into the marsh. For example, from late-October through mid-November 2005, canal inflow was high, outflow was low to moderate, and rainfall was sparse with the exception of the one–day, high rainfall event associated with Hurricane Wilma at the end of October 2005. Following the hurricane and the concomitant canal inflows increases, canal water intrusion was average or above average (Figure 3).

In general, intrusion along the NW and SW transects were above average under high inflows, with the greatest intrusion observed along the SW transect. We suspect that the lower marsh sediment elevation (< 4.9 m) along the SW transect allows canal water to intrude well into the marsh. Even under short periods of inflow (e.g., March 2005), intrusion at the SW transect was above average for two to three days before returning to average.

Influence of Canal and Marsh Stage Difference on Intrusion

The difference between canal and marsh stages influences the distance of canal water intrusion into the marsh. We observed that when canal stages were higher than marsh stages, the distance of intrusion generally increased. An example of this condition was from October through November 2005, when intrusion along all transects was above average. Alternatively, when marsh stages were much higher than canal stages, water tended to move from the marsh towards the canals. Examples of this condition were in July and August 2005, when intrusion at all transects was the lowest observed over the entire study period.

Water from the marsh interior also moves toward the canals when canal stages decrease below marsh sediment elevations. From July through August 2005, marsh stages exceeded the canal stage by 0.3 m or more and canal stages were below marsh sediment elevations (approximately 4.78 m) in the southern end of the study area (Figure 2), resulting in below average intrusion at all transects. Another influence on decreasing intrusion was the increased rainfall during the period (ranging from 0.07–0.24 m). Rainfall, particularly when inflows are low to moderate, can dilute the water column, thus reducing conductivity (USFWS 2007). The combination of low to moderate inflows, moderate to high outflows, and high rainfall led to the lowest intrusion observed during the study period.

It had been previously suggested that when canal stages are at or below 4.72 m, canal water does not move into the marsh (Sylvester 2004). Our study documented canal water intrusion of about 0.3 km when canal levels decreased to 4.72 m, although this intrusion is below average for the study period.

Management Implications

To reduce eutrophic canal water impacts on this historically rainfall-driven marsh, changes to water management operations may be required. These potential changes may be constrained by the need to maintain ecologically appropriate hydroperiods in the marsh and to meet other ecological requirements. First, when flood control or water supply needs lead to inflows, low to moderate inflow rates have the potential to minimize canal water intrusion. However, maintenance of low to moderate inflow rates may not be possible due to unpredictable heavy rainfall events. Second, when inflow rates must be high, the duration of these high inflows should be restricted to less than four days when possible. Understandably, there are conditions during which short duration inflows cannot be maintained, particularly when flood control needs outweigh other management considerations. Third, during periods of extended high inflow (> 4 days), outflow rates equal to or greater than inflow rates can minimize canal stage increases, thus reducing canal water intrusion. Fourth, when canal stages are equal to or higher than marsh stages, intrusion could be reduced by increasing outflows and reducing inflows. Fifth, when canal stages are lower than marsh stages and inflows are necessary, short duration, low to moderate inflows can minimize canal water intrusion.

Minimizing intrusion of polluted canal water is necessary to protect the ecology of the marsh. Other research has shown that exposure of rainfall-driven marsh habitats to canal water causes detrimental changes to marsh flora and fauna. Although this study provides the first comprehensive determination of canal water intrusion, additional studies are needed under a wider range of environmental conditions. Further, coupling the intrusion analyses with ecological (e.g., periphyton and flora and fauna distribution) and other water quality (e.g., phosphorus and calcium) monitoring and research would improve our understanding of the impacts these eutrophic waters have on the wetland and greatly support development of approaches to better protect the marsh. Finally, the interpolated isopleth approach of tracking eutrophic water movement into oligotrophic and mesotrophic systems is applicable to other managed inland aquatic systems (e.g., Maurepas Swamp and Lake Pontchartrain - Louisiana, USA).

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LITERATURE CITED

Brandt, L. A., M. C. Harwell, and M. G. Waldon. 2004. Work plan: water quality monitoring and modeling for the A.R.M. Loxahatchee National Wildlife Refuge. Arthur R. Marshall Loxahatchee National Wildlife Refuge. U.S. Fish and Wildlife Service, Boynton Beach, FL, USA.<http://sofia.usgs.gov/lox_monitor_model/reports/>

Brandt, L. A., K. M. Portier, and W. M. Kitchens. 2000. Patterns of change in tree islands in Arthur R. Marshall Loxahatchee National Wildlife Refuge from 1950 to 1991. Wetlands 20:1–14.

Childers, D. L., R. F. Doren, R. Jones, G. B. Noe, M. Rugge, and L. J. Scinto. 2003. Decadal change in vegetation and soil phosphorus patterns across the Everglades landscape. Journal of Environmental Quality 321:344–62.

Choi, J., J. W. Harvey, and J. T. Newlin. 2003. Significance of microtopography as a control on surface-water flow in wetlands. Greater Everglades Ecosystem Restoration Conference, Palm Harbor, FL, USA.<http://sofia.usgs.gov/geer/2003/posters/microtopo_cntrl/microcntrl.pdf>.

Darby, C. 2004. Comparison of surface water elevations at Refuge staff gauges and USGS gauges. LOX04-007, U.S. Fish and Wildlife Service, Boynton Beach, FL, USA.

Harwell, M. C., D. Surratt, M. G. Waldon, W. W. Walker, and L. A. Brandt. 2005. A.R.M Loxahatchee National Wildlife Refuge enhanced water quality monitoring and modeling: interim report. U.S. Fish and Wildlife Service, Boynton Beach, FL, USA.<http://sofia.usgs.gov/lox_monitor_model/reports/>.

Iricanin, N. 2005. Appendix 4-3: Water year 2004 diel data for STA-1W. *In* G. Redfield (ed.) 2005 South Florida Environmental Report. South Florida Water Management District, West Palm Beach, FL, USA.<http://www.sfwmd.gov/sfer/>.

Kadlec, R. H. 1990. Overland flow in wetlands: vegetation resistance. Journal of Hydraulic Engineering 116:691–706.

McCormick, P. and E. S. Crawford. 2006. Vegetation responses to mineral gradients in an ombrotrophic Northern Everglades peatland, the Arthur R. Marshall Loxahatchee National Wildlife Refuge. Abstract. Greater Everglades Ecosystem Restoration Conference, Orlando, FL, USA.

McCormick, P. V., S. Newman, G. Payne, S. Miao, and T. D. Fontaine. 2000. Chapter 3: Ecological effects of phosphorus enrichment in the Everglades. Everglades Consolidated Report. p. 3.1–3.72. *In* G. Redfield (ed.) South Florida Water Management District, West Palm Beach, FL, USA.<http://www.sfwmd.gov/sfer/>.

McPherson, B. F., B. G. Waller, and H. C. Mattraw. 1976. Nitrogen and phosphorus uptake in the Everglades Conservation Areas, Florida, with special reference to the effects of backpumping runoff. U.S. Geological Survey Water-Resources Investigations Report 76-29. <http://sofia.usgs.gov/publications/wri/76-29/index.html>.

Reddy, K. R., Y. Wang, W. F. DeBusk, M. M. Fisher, and S. Newman. 1998. Forms of soil phosphorus in selected hydrologic units of the Florida Everglades. Soil Science Society of America Journal 62:1134–47.

Richardson, J. R., W. L. Bryant, W. M. Kitchens, J. E. Mattson, and K. R. Pope. 1990. An evaluation of refuge habitats and relationships to water quality, quantity, and hydroperiod: a synthesis report. Florida Cooperative Fish and Wildlife Research Unit, University of Florida, Gainesville, FL, USA.

Scheidt, D., J. Stober, R. Jones, and K. Thornton. 2000. South Florida ecosystem assessment: Everglades water management, soil loss, eutrophication and habitat. EPA 904-R-00-003, U.S. Environmental Protection Agency. <http://www.epa.gov/region4/sesd/sesdpub_completed.html>.

Sklar, F. H., K. Rutchey, S. Hagerthy, M. Cook, S. Newman, S. Miao, C. Coronado-Molina, J. Leeds, L. Bauman, J. M. Newman, M. Korvela, R. Wanvestraut, and A. Gottlieb. 2005. Chapter 6: Ecology of the Everglades Protection Area. p. 6.1–6.43. *In* G. Redfield, S. Efron, and K. Burns (eds.) 2005 South Florida Environmental Report. South Florida Water Management District, West Palm Beach, FL, USA.<http://www.sfwmd.gov/sfer/>.

Stober, J., D. Scheidt, R. D. Jones, K. Thornton, L. Gandy, D. Stevens, J. C. Trexler, and S. Rathbun. 1998. South Florida Ecosystem Assessment: Final Technical Report — Phase I. EPA 904-R-98-002. U.S. Environmental Protection Agency Region 4, Science and Ecosystem Support Division, Athens, GA, available at: http://www.epa.gov/region4/sesd/reports/epa904r98002.html.

Stober, Q. J., K. Thornton, R. D. Jones, J. Richards, C. Ivey, R. Welsh, M. Madden, J. C. Trexler, E. E. Gaiser, D. Scheidt, and S. Rathbun. 2001. South Florida Ecosystem Assessment: Phase I/II Technical Report – Everglades stressor interactions: hydropatterns, eutrophication, habitat alteration, and mercury contamination. EPA 904-R-01-003, Athens, GA, USA.<http://www.epa.gov/region4/sesd/reports/epa904r01002.html>.

Swift, D. R. 1981. Preliminary investigations of periphyton and water quality relationships in the Everglades Water Conservation Areas: February 1978 – August 1979. DRE-131, South Florida Water Management District, West Palm Beach, FL, USA.

Swift, D. R. 1984. Periphyton and water quality relationships in the Everglades Water Conservation Areas. Environments of South Florida Present and Past II, P. J. Gleason (ed.) Miami Geological Society, Coral Gables, FL. p. 97–117. <http://mwaldon.com/Loxahatchee/GrayLiterature/Swift-1984.pdf>.

Sylvester, S. 2004. Unpublished. Discussion sheet: Water Conservation Area 1 (WCA-1) canal water level for water supply. U.S. Army Corps of Engineers, Jacksonville, FL.

USFWS. 2000. Arthur R. Marshall Loxahatchee National Wildlife Refuge Comprehensive Conservation Plan. U.S. Fish and Wildlife Service, Boynton Beach, Florida, USA.<http://loxahatchee.fws.gov>.

USFWS. 2007. Arthur R. Marshall Loxahatchee National Wildlife Refuge — Enhanced Monitoring and Modeling Program Annual Report. LOX06-008, U.S. Fish and Wildlife Service, Boynton Beach, FL, USA.<http://sofia.usgs.gov/lox_monitor_model/reports/>.

USGS. 2005. Digital elevation map — A.R.M. Loxahatchee National Wildlife Refuge. United States Geological Services, FL, USA.<http://sofia.usgs.gov/exchange/desmond/desmondelev.html>.

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